OPTICAL METROLOGY FOR *STARLIGHT* SEPARATED SPACECRAFT STELLAR INTERFEROMETRY MISSION

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ABSTRACT – *We describe a high-precision inter-spacecraft metrology system designed for NASA's StarLight mission, a space-based separated-spacecraft stellar interferometer. It consists of dual-target linear metrology, based on a heterodyne interferometer with carrier phase modulation, and angular metrology designed to sense the pointing of the laser beam and provides bearing information. The dual-target operation enables one metrology beam to sense displacement of two targets independently. We present the current design, breadboard implementation of the Metrology Subsystem in a stellar interferometer testbed and the present state of development of flight qualifiable subsystem components*

1. Description of the *StarLight* Mission

NASA's *StarLight* mission was designed to be a formation-flying optical interferometer in space. The goal of the mission was to demonstrate the technology that will be needed for future astrophysics missions, such as the Terrestrial Planet Finder (TPF). The StarLight mission was scheduled for a 2006 launch; however, the flight development activities of StarLight were terminated in March 2002 (late in the System Definition Phase). By that time most optical metrology system design and the metrology technology demonstration activities were completed. Since then, the StarLight project has been merged with the TPF and will continue to develop ground technologies for formation-flying interferometry. In this paper we will describe a metrology subsystem of *StarLight* which is currently baselined as a basis for TPF metrology.
The Metrology subsystem enables very precise determination of relative velocity between the spacecraft, relative displacements and inter-spacecraft pointing. It consists of long-range dual-target linear metrology and angular metrology designed to sense the pointing of the laser beam. The dual-target operation allows one metrology beam to sense displacement of two targets independently and therefore enables one system to serve as both internal optical pathlength disturbance sensor and inter-spacecraft range rate sensor. We present the current design, breadboard implementation of the Metrology Subsystem in a stellar interferometer testbed and the present state of development of flight qualifiable subsystem components
The two spacecraft configuration has a projected baseline that varies between 30 and 125 m as the separation is increased from 40 to 600 m. The collector spacecraft relays the incoming starlight to the combiner spacecraft, where it is combined with light that enters the combiner directly. To obtain an interference pattern, the two paths from the star to the beam combiner must be equalized to a fraction of a micron. A variable delay line is used to actively compensate for the small motions of the spacecraft sensed by the metrology systems. Further details can be found in references [1, 2]. The metrology system serves four primary purposes: (1) Measure the rate of change of the separation between the spacecraft, i.e. the range rate. A separate RF sensor is used to measure the absolute range. (2) Measure the position of the variable delay line. (3) Measure any high frequency jitter in the optical path lengths through the system. (4) Provide a sensor to acquire and ensure that the left boresight of the Combiner is always pointed at the center of the Collector optics, i.e. inter-spacecraft bearing. The Linear Metrology system addresses (1), (2), and (3); the Angular Metrology system addresses (4).

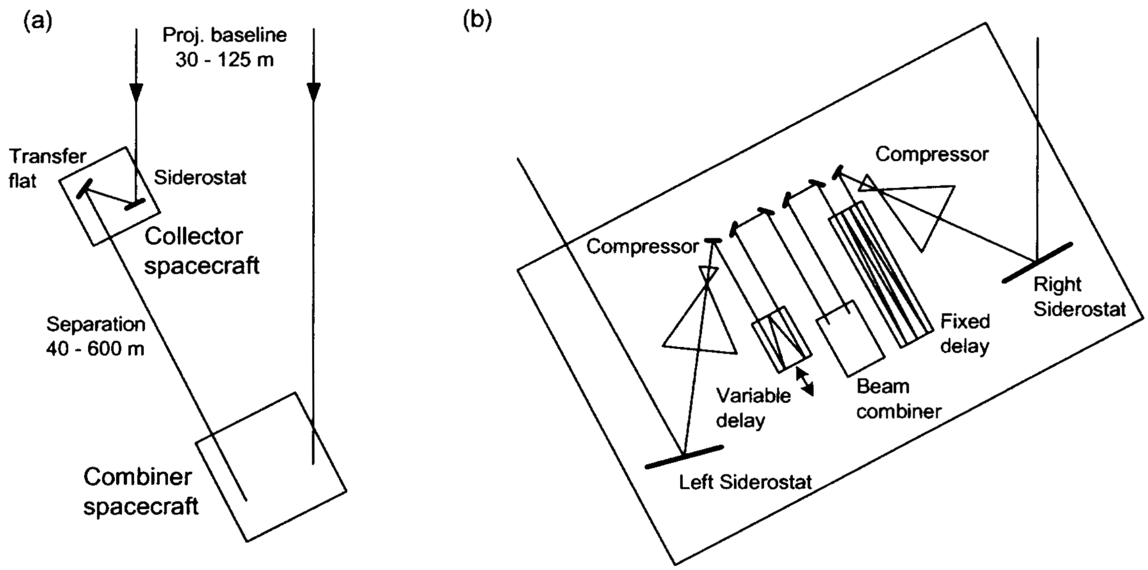


Figure 1. (a) Schematic formation configuration. (b) Combiner optics schematic.

2. Challenges and Implementation Choices

Interspacecraft operation inherent in Formation Flying missions creates unique challenges for the metrology subsystem and these challenges drove the implementation choices made in the design of the metrology subsystem.

Major challenges for the StarLight metrology that drove its implementation choices were

a) Measurement of nanometer level displacements over hundreds of meters target distances with limited beam apertures.

Nanometer-level resolution caused the choice of optical heterodyne interferometer as a basis for the metrology gauge. Large target distance with a limited metrology beam aperture meant that the system had to operate with very high optical losses. Regular heterodyne interferometers cannot operate well with high optical losses in the target path due to a parasitic effect called self-interference and therefore a modification called heterodyne interferometer with carrier phase modulator was introduced[3]. The functionality of this modification was subsequently absorbed into the dual-target metrology[4, 5].

Nanometer-level resolution over hundreds of meters target ranges also demands a use of a very frequency-stable optical source. The laser and the frequency stabilization system are described in Section 5.

b) Displacement measurements of two independent targets along the same line of sight

The present StarLight configuration requires independent measurements of optical pathlength changes inside the combiner (intra-spacecraft) and pathlength changes between the combiner and collector (inter-spacecraft). A standard method would have been to deploy two single target linear metrology gauges, however a more elegant method called "dual-target metrology" was found[4, 5]. It reduces the amount of necessary hardware and removes the need for co-alignment of two gauges. It also suppresses self-interference.

c) High-precision pointing

Metrology subsystem is also used to acquire the collector aperture in the left combiner boresight of the stellar subsystem and subsequently serves as the sensor for pointing jitter. Stellar pointing control loop is closed around the Metrology Pointing Sensor. The Metrology Pointing Sensor was implemented as an Intensity Gradient Detector (IGD) and it's design was driven by the tradeoff between acquisition range and pointing resolution. The IGD design and performance evaluation are described in Section 5

d) Flight qualifiable implementation

To simplify system integration and reliability we chose to implement the system with fiber-pigtailed components. Each component has fiberoptic input and/or output and fusion splices and/or fiber connectors are used for components interconnects. The designs of key components are described in section 5.2

3. Metrology Subsystem Functionality

The *StarLight* metrology system is based on an optical heterodyne interferometer gauge. It uses changes in the optical phase of a laser beam propagating between fiducial and target reflectors to detect disturbances the optical pathlength between the two targets. A sensor similar to a quad-cell is used to detect offsets in the pointing of the laser beam.

A top-level functional block diagram of the Metrology subsystem is shown in Figure 2. The Metrology Source, containing a laser and associated optoelectronics, supplies properly prepared optical beams to Metrology Optics. Metrology Optics are used to route the left and right laser beams between the fiducial point F, located near the interferometer beamsplitter, and the three targets: A, B and C. On the right side, metrology senses optical pathlength disturbances inside the combiner spacecraft, Right Intra-Combiner disturbances. On the left side the Metrology independently senses the pathlength disturbances inside the combiner spacecraft (Left Intra-Combiner disturbances) and pathlength changes due to spacecraft separation (Inter-Spacecraft disturbances). The Metrology Pointing Sensor determines the shear of the beam relative to sensor's center and therefore senses disturbances in the beam pointing. The centroid information, Δx and Δy, is transmitted back to the Combiner spacecraft via an RF link.

The Metrology System can be broken into two functional elements: Linear Metrology and Angular Metrology, sensitive to the observables shown in Table 1. The metrology measurands are then used by the Instrument to calculate quantities shown in the Metrology tasks column.

The linear part of StarLight Metrology is implemented as a heterodyne interferometer with dual-target capability. The dual-target concept, described in the subsequent section, is a novel interferometer architecture developed at JPL in response to the needs of the StarLight mission [5]. The parabolic geometry of the StarLight stellar interferometer [6] demands that the intra-combiner and inter-spacecraft pathlength disturbances on the Left side be known independently. The dual-target architecture enables us to measure two targets with a single gauge.

The angular part of the StarLight Metrology consisting of a Metrology Pointing Sensor implemented as an intensity gradient detector mounted on the Collector Transfer Flat. It is essentially a quad-cell consisting of four separated photodetectors.

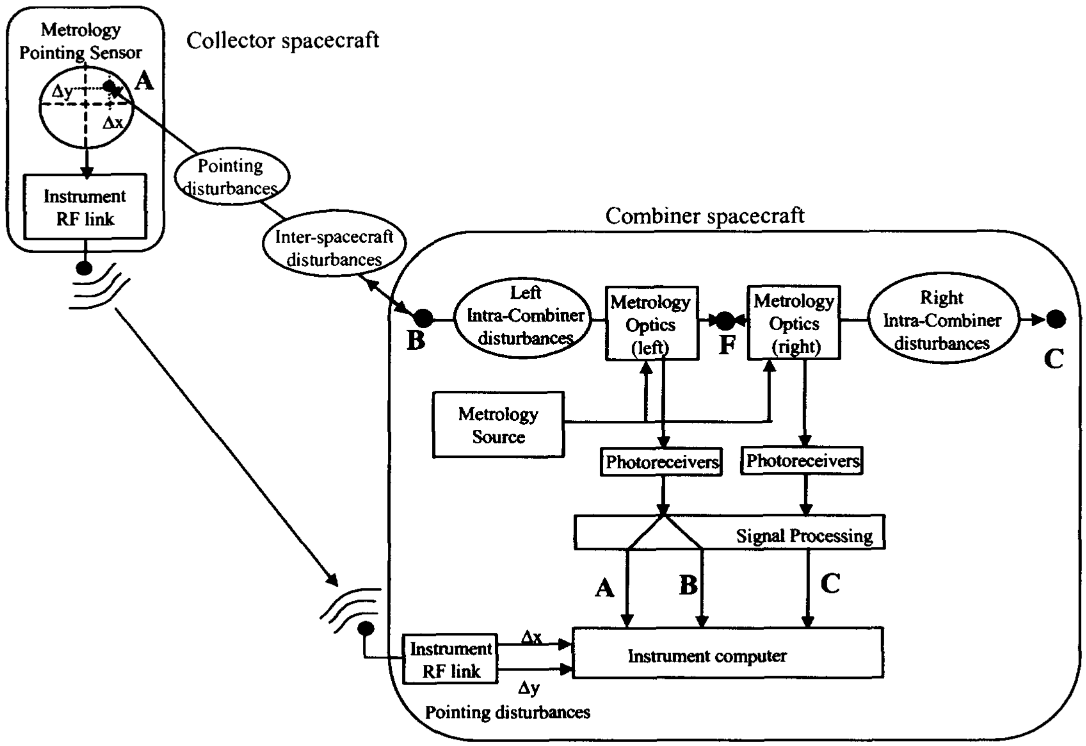


Figure 2. Top level functionality of Metrology subsystem

Table 1. Connection between Metrology functional elements, measurands, requirements and tasks.

Metrology tasks	Measured disturbance	Observable	Requirement	
(1) measure the range rate	Left Inter-Spacecraft disturbances	AF-BF	120 um/sec	Linear Metrology
(2) measure position of the variable delay line	Left Intra-Spacecraft disturbances	BF	11 nm 1-σ in 10-1000 Hz BW	
(3)measure high frequency jitter in the optical path lengths through the system.	Inter-Spacecraft disturbances and Right Intra-Combiner disturbances	AF, BF, CF	11 nm 1-σ in 10-1000 Hz BW	
(4) measure Combiner boresight pointing	Pointing Disturbances	Δx, Δy	<18 mas 1-σ within 118 Hz	Angular Metrology

4. Metrology System Implementation

The schematic of the StarLight metrology system implementation is shown in Figure 3. The Right Intra-Combiner Metrology is a standard heterodyne metrology gauge. On the left side the dual-target architecture enables a single gauge to serve as both Left Intra-Combiner Metrology and Inter-Spacecraft Metrology.

A narrow-linewidth fiber-coupled laser is used as the optical source for the interferometer. It is split into the Local and Target paths. Frequency Shifters are used to create a frequency difference between the two paths equal to the desired heterodyne frequency (10 kHz). Two frequency shifters are used, because existing optical frequency shifters operate at multi-megahertz frequencies, whereas we desire a kilohertz heterodyne frequency. A Phase Modulator in the Target path is used to enable the dual-target operation on the left side. The inherent laser frequency stability is not sufficient to enable the required 11-nanometer resolution at a 600 meter target distance, so we use an external frequency

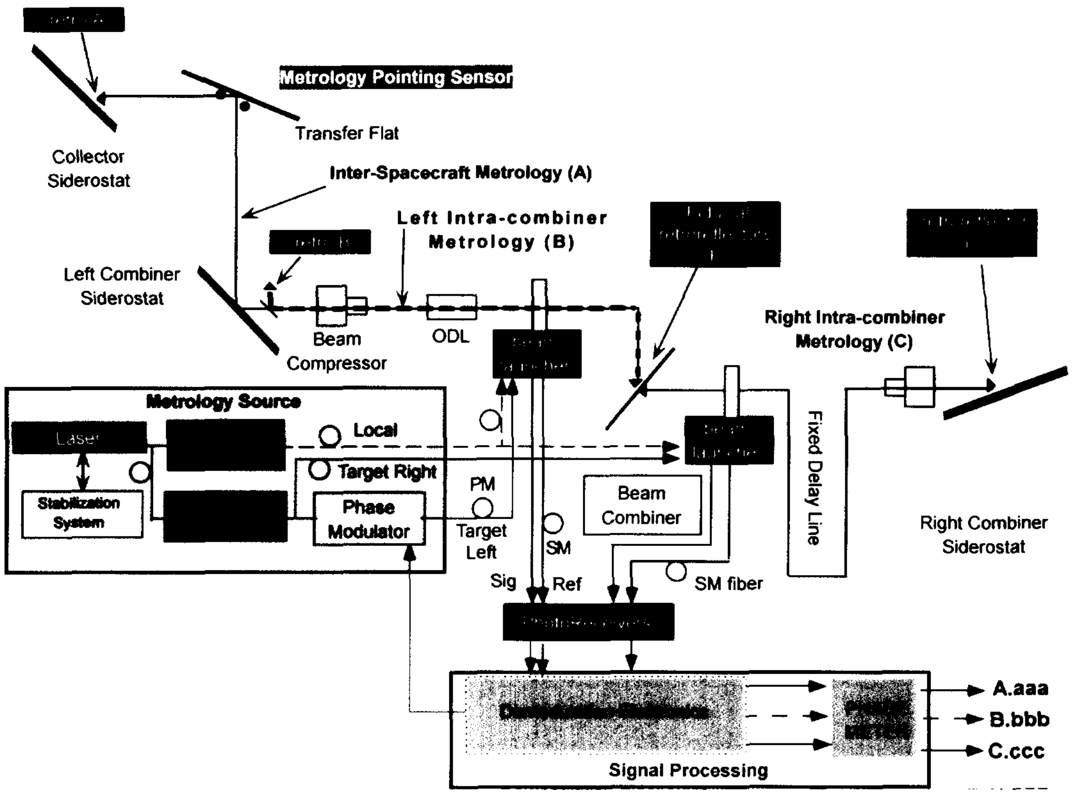


Figure 3. Metrology subsystem implementation

Stabilization System. The Metrology Source, consisting of the above components, is then connected via polarization maintaining fibers to the Beam Launchers. The Beam Launchers collimate the fiber output and direct the Target metrology beam along the boresight of the stellar beam. The metrology beams are returned back to the beamlauncher by the retroreflectors. At the Beam Launcher the returning Target beams are combined with a Local beam in a single mode fiber and taken to the remotely located photoreceivers. The electronic signals are subsequently demodulated into three independent heterodyne signals and the desired heterodyne phase shifts are measured by the Phase Meter. The three outputs of the Phase Meter are used to detect changes in the optical pathlength to the three targets A, B, and C.

The Metrology Pointing Sensor is implemented as an Intensity Gradient Detector mounted on the Collector Transfer Flat. It is essentially a quad-cell consisting of four separated photodetectors.

5. Linear Metrology

The linear part of StarLight Metrology is implemented as a heterodyne interferometer with dual-target capability. The dual-target concept, described in the subsequent section, is a novel interferometer architecture developed at JPL in response to the needs of the StarLight mission [5]. The parabolic geometry of the StarLight stellar interferometer [6] demands that the intra-combiner and inter-spacecraft pathlength disturbances on the Left side be known independently. The dual-target architecture enables us to measure two targets with a single gauge.

5.1 Dual Target Metrology Concept

The StarLight linear metrology system operates at 1320 nm, with independent gauges to monitor the left and right optical paths through the instrument.

The right gauge is a standard heterodyne metrology gauge. The left gauge monitors both the path internal to the combiner (from the beam combiner out to the left combiner siderostat) and the external path (from the left combiner siderostat to the collector siderostat). A novel phase modulation scheme

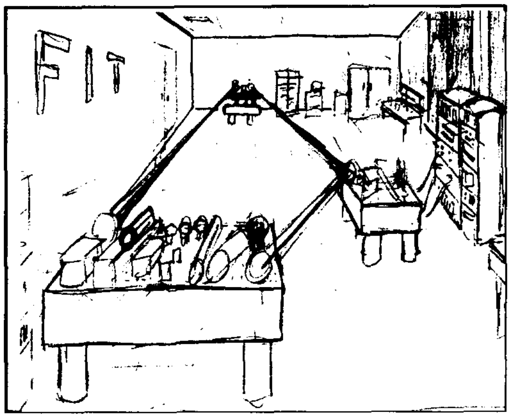


Figure 4. Operation of the metrology subsystem in the Formation Interferometer Testbed

allows us to separate the signal returns from two retro-reflectors , one located near the left combiner siderostat, the other on the collector siderostat (Fig. 1b). The dual target metrology is described in more detail in reference [4, 5]. The technique also suppresses the self-interference error due to polarization leakage.

This system has been successfully tested in the lab and a turn-key prototype has been delivered to the Formation Interferometer Testbed (FIT) where it supports fringe acquisition and tracking. The FIT, illustrated in Figure 4a, simulates the combiner and collector spacecraft with two optical benches. The combiner bench is mounted on a hexapod so that spacecraft motion can be simulated. The Metrology hardware, illustrated in Fig. 4b, has been fully integrated into the testbed and meets its performance requirements.

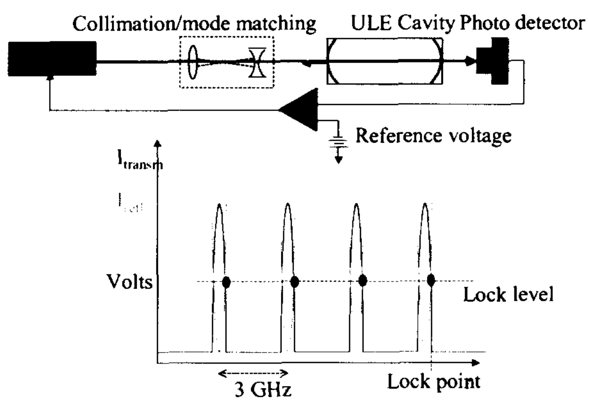
5.2 Linear Metrology Components

We are currently working on developing components and integration techniques that will allow us to implement a space qualified version of the system. To simplify system alignment and therefore improve its reliability we chose to interconnect most of the components using polarization maintaining fibers[7]. Each component is pigtailed with input and output fibers that are fusion spliced together. Fusion splices have negligible loss and polarization degradation. Fiberoptic interconnects greatly simplify the testing and integration process by completely removing any need for inter-component alignment, significantly simplify the space-qualification process, and save weight and size compared to a stable optical bench and mounts. Even for laboratory use, fiberoptic integration leads to much lower integration costs, especially in terms of time, pain and suffering, although the cost for individual components may be higher.

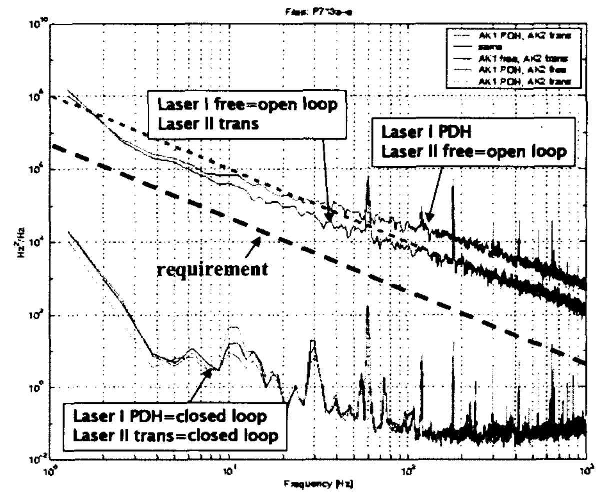
Subsequent sections describe each of the components in its current state of development.

5.2.1 Laser

The laser for the StarLight metrology system needs to satisfy both rigorous functional and environmental requirements. In particular, the wavelength is required to be greater than 1.1 μm so that metrology light does not contaminate the visible starlight signal. Inter-spacecraft operation requires that the laser must provide high optical power (> 200 mW) to compensate for high losses and its frequency characteristics must be such that optical frequency noise can be kept below 100 Hz/root(Hz) between 10 and 1000 Hz to ensure 11 nanometer resolution over a 600 meter target range. If the laser is not quiet enough on its own, this can be obtained by locking the laser to an external cavity, i.e. the laser must be tunable.



b)



a)

Figure 5. a) Illustration of the transmission lock concept, b) Experimental results

We chose a Nd:YAG Non-Planar Ring Oscillator (NPRO) laser operating at 1.32 um wavelength as the baseline laser for the metrology system. The testbed demonstrations have been implemented with commercial lasers from Lightwave Electronics Corp. The flight version of the system requires much greater reliability and lifetime. We have therefore, with support from Lightwave Electronics, developed a completely re-designed version of the NPRO laser, with laser welding of all critical-alignment components and a drastic reduction of the internal optical paths [8]. Another innovation is that the pump light is delivered to the Nd:YAG crystal via a multimode fiber through a specially designed ferrule that accommodates up to three pump diodes{Dubovitsky, 2001 #344}. The ability to pump a single crystal with three diodes greatly enhances the reliability and lifetime of the laser and/or enables high power output.

4.2.2 Frequency Stabilization System

Currently our free-running lasers do not meet the frequency stability requirements of the mission (100 Hz/root(Hz) between 10 and 1000 Hz). Therefore an external frequency stabilization system is used. Because we need only a modest improvement in the frequency stability, we plan to use a simple transmit/reflect architecture in which the laser frequency is locked to the side of the cavity resonance peak [9].

The frequency stabilization system measures the transmitted light portion of a Fabry-Perot cavity and compares it to a stable reference voltage to generate the feedback signal. The principle is shown in Figure 5a. This signal is controlling the laser frequency using the laser PZT ("fast") and crystal temperature ("slow") actuators, therefore keeping the light level on the photo detector constant. According to Figure 5a this is equivalent to keeping the laser frequency stable. Because this system measures the transmitted light level it is sensitive to laser power fluctuations. One remedy to this problem is to monitor the reflected light from the cavity as well and use the ratio transmitted/reflected as the sensor signal.

Frequency noise measurements were done on our breadboard experiment by beating the stabilized laser light with the light from a second laser that was frequency stabilized using the Pound-Drever-Hall stabilization [10]. We used two methods to measure the residual frequency noise, a frequency discriminator based on a delay line [11] and a Time-Frequency analyzer (HP5371A). The results of the frequency discriminator measurements are shown in Figure 5b. The frequency discriminator measurements do agree well with the data taken with the Time-Frequency analyzer.

6. Angular Metrology

The purpose of the angular metrology is to provide a sensor to ensure that the left boresight of the Combiner is always pointed at the center of the Collector optics. The Metrology Pointing Sensor is implemented as an Intensity Gradient Detector (IGD) shown in Fig. 6a. It consists of four photodiodes mounted at the center of the Collector transfer flat (Fig. 1a), with a separation of 2 cm. The linear metrology laser light incident on the IGD from the Combiner has a Gaussian intensity distribution and nominally illuminates the photodiodes as shown in Fig. 6a. When the metrology beam is centered on the IGD array, all the detectors see equal intensity and produce identical output signals. If the beam pointing changes on the Combiner it will be observed as a beam shear at the Collector, and the outputs of the IGD detectors will no longer be balanced. By differencing the detector outputs pair-wise and normalizing by the pair-wise sum we can determine the direction and magnitude of the beam displacement from the Collector optical axis.

The photocurrents from the four photodiodes can be used in a variety of ways to infer the position of the beam. One particularly convenient set of variables consists of Δx and Δy defined in fig. 6b. The advantage in using these variable stems from the fact that their functional dependence on the corresponding beam coordinates is particularly simple and can be well approximated well using a simple odd-order polynomial, e. g. a cubic. This simplifies the calibration of the sensor.

The spatial resolution of the sensor depends on the slope of the curve in Fig. 6b and on the unavoidable noise contributions to the photocurrents.

The slope of the variables Δx and Δy versus the corresponding beam coordinate depends on the size of the pattern defined by the four photodiodes, which is fixed, and on the beam diameter, which varies with the distance from the beam launch point. The two main noise contributions are:

1. Photon shot noise, which is proportional to the square root of the photocurrents. The photocurrents in turn are proportional to the amount of light incident on the photodiodes, which is a function of distance from the beam launch point.
2. Electronics noise is generated by dark current at the photodiodes and by the preamplifiers. This contribution does not depend on position along the beam.

Knowledge of the inter-spacecraft distance enables us to convert the error in transverse beam position measurement into a pointing error signal for the combiner siderostat. The noise contributions discussed above and the total resulting limitation in sensor resolution are shown in Fig. 6c in units of beam pointing error. As the plots show, the resolution of the pointing sensor is adequate for *StarLight*, with sufficient margin

7. CONCLUSIONS

We have implemented a prototype and demonstrated on the ground a metrology system for NASA's *StarLight* mission. The system consists of a novel dual-target linear system and angular metrology for maintaining the pointing. The StarLight metrology subsystem demonstrates key performance features needed for the Terrestrial Planet Finder and will be used a foundation for the TPF metrology design.

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with a National Aeronautics and Space Administration.

REFERENCES

[1] O. P. Lay, G. H. Blackwood, S. Dubovitsky, P. W. Gorham, and R. P. Linfield, "Design of the ST 3 Formation Flying Interferometer," presented at Optical IR Interferometry from Ground and Space, Dana Point, CA, 1999.

[2] R. M. Duren and O. P. Lay, "The *StarLight* formation-flying interferometer system architecture," presented at IEEE Aerospace Conference, Big Sky, MT, 2002.

[3] S. Dubovitsky, O. P. Lay, and D. J. Seidel, "Elimination of heterodyne interferometer nonlinearity by carrier phase modulation," *Opt. Lett.*, vol. 27, pp. 619-621, 2002.

[4] O. Lay and S. Dubovitsky, "Dual target metrology," presented at Spring Topical Meeting of American Society for Precision Engineering on Interferometric Metrology, Tucson, AZ, 2000.

[5] O. Lay and S. Dubovitsky, "Dual target metrology," *NASA Tech Briefs*, vol. 25, pp. 12a-14a, NPO-21032, 2001.

[6] P. W. Gorham, W. M. Folkner, and G. H. Blackwood, "Eabling concepts for the dual spacecraft formation-flying optical interferometer for NASA's ST3 mission," presented at Optical IR Interferometry from Ground and Space, Dana Point, CA, 1999.
[7] S. Dubovitsky, D. J. Seidel, D. T. Liu, and R. C. Gutierrez, "Metrology source for high-resolution heterodyne interferometer laser gauges," presented at SPIE International Symposium on Astronomical Telescopes and Instrumentation, Kona, Hawaii, 1998.
[8] D. Lui, "Laser welded fiber-pigtailed NPRO laser," *NASA Tech Briefs*, vol. 25, pp. 12a, 2001.
[9] D. White, "Frequency Stabilization of gas lasers," *IEEE J. Quantum Electron.*, vol. 1, pp. 349-357, 1965.
[10] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, "Laser phase and frequency stabilization using an optical resonator," *Appl. Phys. B*, vol. 31, pp. 97-105, 1983.
[11] A. Tykulsky, "Spectral measurements of Oscillators," *Proceedings.of the IEEE*, pp. 306, 1965.

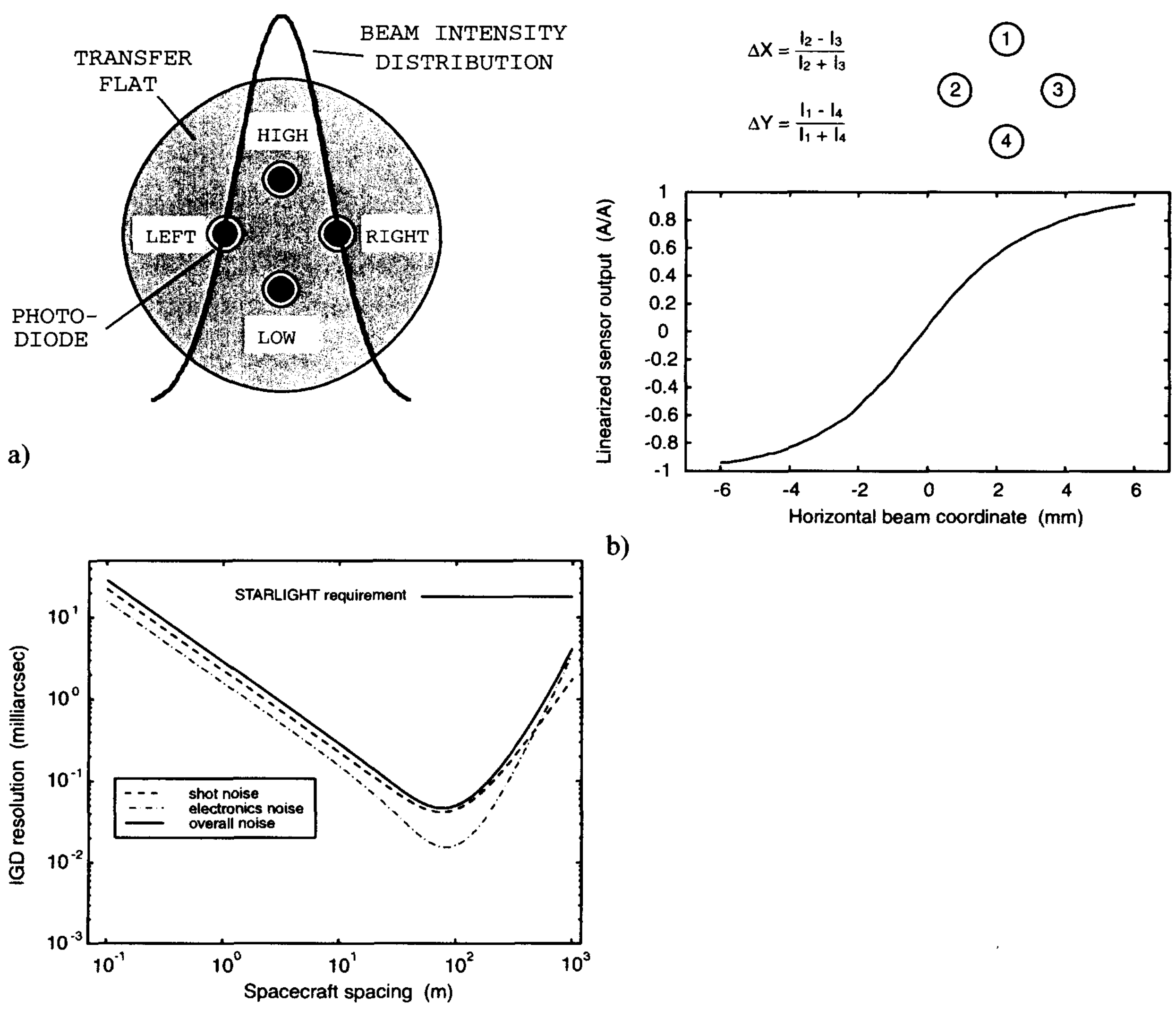


Figure 6 a) Intensity Gradient Detector (IGD) principle of operation, b) IGD transfer function, c) experimental results